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CAPTURES OF RED GIANT STARS BY BLACK HOLES IN ELLIPTICAL GALAXIES: FEEDBACK TO THE HOT GAS

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ABSTRACT

The highly disturbed hot gas in elliptical galaxies, as revealed in many *Chandra* X-ray images, implies a source of energy in the galactic nucleus. In some elliptical galaxies faint X-ray "ghost" cavities appear without corresponding radio lobes. It has been suggested that ghost cavities are caused by short-lived activity with a timescale of $\sim 10^3-10^4$ years, but this is difficult to understand within the popular paradigm of active galactic nuclei. We suggest an episode model for ghost cavities, invoking captures of red giant stars by the black hole located at the center of the elliptical galaxies at a typical rate of 10^{-5}yr^{-1} per galaxy. The accretion of tidally disrupted red giant stars onto the black hole powers activity in a timescale of a few years. The total energy channeled into the jet/outflow during the cooling time of the hot gas is $\sim 10^{56}$ erg, which is the typical work required to form the observed cavities. In this scenario, the faint cavities are produced by the feedback following accretion of the debris of the captured red giant stars onto the black holes. We apply the present model to several elliptical galaxies and find that it can explain the formation of the ghost cavities. This model can be tested in the future by comparisons between radio and X-ray observations.

Subject headings: galaxies: active - X-rays: galaxy

1. INTRODUCTION

Black holes located in the centers of galaxies inevitably capture stars (Hills 1975; Rees 1988) if the tidal energy dissipated in the stellar envelope exceeds its orbital energy with respect to the black hole. For a main sequence star of mass M_* and radius R_*, the captures occur at a tidal radius, $R_{\rm T} \approx R_* \left(M_{\rm BH}/M_*\right)^{1/3}$, which is beyond the last stable orbit of a black hole with mass $M_{\rm BH} \leq 2\times 10^8 M_\odot$. Such capture events occur every $\sim 10^4$ years (Rees 1988). A fraction of the gas released by the disruption of the stars remains bound to the black hole and eventually will be accreted. This process would create bright flares in optical, UV and soft X-ray with a timescale of a few years (Rees 1988; Cannizzo et al. 1990; Loeb & Ulmer 1997). *Chandra* observations with high spatial resolution of the nonactive galaxy RX J1242.6-1119A show striking evidence for the capture process (Komossa et al. 2004) and a growing body of evidence provides further support for such captures (Halpern et al. 2004).

Larger black holes, $M_{\rm BH} \geq 2\times 10^8 M_\odot$, can entirely swallow a captured main sequence star with very little radiative losses. However, giant stars can be tidally disrupted by the black hole beyond the last stable orbit since their densities are much lower than main sequence stars (Syer & Ulmer 1999). Therefore the debris of captured red giants will significantly radiate its gravitational binding energy as it accrets onto the black hole. Although the energy released by each red giant capture is small, the total energy released during the lifetime of the galaxy is quite large, extending to $> 10^{56}$ erg if some of the released energy can be piled up before the gas cools. An interesting question arises: Can the capture of red giant stars significantly influence the hot gas in these galaxies?

It is well-known that elliptical galaxies contain significant amounts of hot gas originally found by *Einstein* (Forman et al. 1985; see a review of Mathews & Brighenti 2003). It has been suggested that the hot gas can be disturbed in two ways: (1) by internal processes such as nuclear outbursts; and (2) externally by galaxy-galaxy and galaxy-cluster interactions. In this Letter we are only concerned with the first case. When powerful radio jets interact strongly with the hot gas very clear features of cavities, hot spots etc. should appear, as in MS 0735.6+7421 (McNamara et al. 2005), where the radio lobes fill the X-ray cavities. However, faint "ghost" X-ray cavities are also observed in the absence of powerful radio sources. For example, NGC 4636, a well-known non-active galaxy without radio lobes, has an extensive, highly disturbed X-ray halo containing ghost cavities (Jones et al. 2002; Ohto et al. 2003). This strongly implies a very short timescale for the activity of the black hole in this galaxy, 10^3-10^4 years. Observations typically constrain the lifetime of active galactic nuclei to 10^6-10^8 years (Martini 2004), but such long-term activity cannot apply to NGC 4636. What powers such short-lived activity on galactic scales?

In this paper we focus on the capture of red giant stars by black holes of mass $> 2\times 10^8 M_\odot$. We show that the accretion of stellar debris onto the black holes produces an energy feedback into the galactic hot gas that can explain the formation of X-ray ghost cavities.

2. RED GIANT STAR CAPTURE PROCESS AND FEEDBACK

2.1. *Star-capture rates of the black holes*

In their study of the capture rate of red giant stars by massive galactic black holes, Syer & Ulmer (1999) made the following assumptions: 1) a virialized star cluster; 2) a simple model of stellar evolution; 3) a Salpeter mass function for the stars; and 4) the maximum radius of red giant stars is determined by collisions with main sequence stars. For a Salpeter IMF a fraction 0.05 of stars are red giants. The maximum radius of the red giant stars, $200R_\odot$, is attained only during a short phase (10%) of their evolutionary lifetime. The mean radius of red giant stars is $\bar{R}_* = 12R_\odot$. The average tidal radius under a Newtonian po-

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tential is given by

$$\frac{\bar{R}_{\rm T}}{R_S} = \frac{\bar{R}_*}{R_S}\left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} = 26.3\, m_*^{1/3} M_8^{-2/3} r_*, \tag{1}$$

where $R_S = GM_{\rm BH}/c^2$ is the Schwarzschild radius of the black hole, $r_* = \bar{R}_*/12R_\odot$ and $m_* = M_*/M_\odot$ are respectively the radius and mass of the captured star, and $M_8 = M_{\rm BH}/10^8 M_\odot$ is the mass of the black hole.

Since the radius of the red giant star is much larger than that of main sequence stars, the loss cone will be enlarged by a factor of $R_{\rm max}/R_\odot$. A detailed calculation of the red giant capture rate by Syer & Ulmer (1999) depends on a large number of parameters: star density profile, total number of stars, Salpeter mass function, the maximum radius of the red giant stars, the black hole mass and the time-dependent radius of the red giant stars. However, a simplified version of the capture rate can be obtained by fitting the data in Syer & Ulmer (1999),

$$\dot{N}_{\rm RG} \approx 10^{-5}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{0.35} {\rm yr}^{-1}, \tag{2}$$

where other parameters are fixed. This approximation is reasonably good for more massive galaxies where $M_{\rm BH} \geq 10^8 M_\odot$.

2.2. *Impulsive Feedback Heating*

The detailed capture process and relevant radiation from the bound gas have been studied by several authors (e.g. Rees 1988; Cannizzo et al. 1990; Loeb & Ulmer 1997; Ulmer 1999). We follow treatments in Loeb & Ulmer (1997) and Ulmer (1999). Once a red giant star is tidally disrupted, a fraction ξ of its gas remains bound to the BH. This gas will return to the pericenter after a time $t_{\rm min}$ (Ulmer 1999)

$$t_{\rm min} \approx 45.7\, r_*^{3/2} m_*^{-1} M_8^{1/2}\left(\frac{R_p}{\bar{R}_{\rm T}}\right)^3 {\rm yr}, \tag{3}$$

where R_p is the pericenter radius of the captured star ($R_p \sim \bar{R}_{\rm T}$). The gas enters a circular orbit around the BH and forms an accretion disk within a timescale

$$t_{\rm cir} = n_{\rm orb} t_{\rm min} \approx 91.5\left(\frac{n_{\rm orb}}{2}\right)\left(\frac{t_{\rm min}}{45\ {\rm yr}}\right) {\rm yr}, \tag{4}$$

where $n_{\rm orb}$ is a small number of orbits necessary for circularization (Ulmer 1999). Subsequently, a thick torus or thin disk will form, depending on accretion timescale $t_{\rm acc}$ and radiation timescale $t_{\rm rad}$ (the time to radiate all of the energy released by the debris at the Eddington luminosity; Loeb & Ulmer 1997). If $t_{\rm acc} \gtrsim t_{\rm rad}$, a thin disk will form, otherwise, a torus. Using the parameterized viscosity through the relation $\eta = \alpha P_{\rm rad}\Omega_{\rm K}^{-1}$, where α is the viscous constant and the Keplerian velocity $\Omega_{\rm K} = (GM_{\rm BH}/R^3)^{1/2}$(Shakura & Sunyaev 1973), we find the debris of the captured star will be swallowed by the black hole within a time

$$t_{\rm acc} \approx \frac{\rho_{\rm gas}\bar{R}_{\rm T}^2}{\eta} \approx 0.8\, M_8 \alpha_{-2}^{-1}\left(\frac{r_{\rm T}}{25}\right)^{3/2} {\rm yr}, \tag{5}$$

where $\alpha_{-2} = \alpha/10^{-2}$ and $r_{\rm T} = \bar{R}_{\rm T}/R_S$ (Eq. 20 in Loeb & Ulmer 1997). The radiation time is

$$t_{\rm rad} = \frac{\xi\epsilon m_* M_\odot c^2}{L_{\rm Edd}} \approx 0.21\, \xi_{0.5} m_* M_8^{-1}\epsilon_{0.1}\ {\rm yr}, \tag{6}$$

where $\epsilon_{0.1} = \epsilon/0.1$ is the the accretion efficiency and $\xi_{0.5} = \xi/0.5$. We find $t_{\rm acc} > t_{\rm rad}$, therefore a thin disk forms. The structure of the disk is determined by the Eddington ratio defined by $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ where $\dot{M}_{\rm Edd} = 2.2\epsilon_{0.1}^{-1} M_8\ M_\odot$/yr, therefore

$$\dot{m} \approx \frac{\xi M_*}{t_{\rm acc}\dot{M}_{\rm Edd}} \approx 0.3\, \xi_{0.5} m_* M_8^{-1}. \tag{7}$$

The disk formed by the debris corresponds to the inner region of the standard disk unless the accretion timescale is much shorter than $t_{\rm rad} \sim 0.21$yr. From the standard accretion disk model (Shakura & Sunyaev 1973), we find $P_{\rm rad}/P_{\rm gas} = 3.9\times 10^2 (\alpha_{-2}M_8)^{1/4}\left(r_{\rm T}/25\right)^{-21/8}\dot{m}_{-1}^2 \gg 1$, where $\dot{m}_{-1} = \dot{m}/0.1$, so the radiation pressure dominates the gas in the debris disk.

It has been suggested that most of the black holes in the universe are rapidly spinning (Elvis et al. 2002; Volonteri et al. 2005). The energy channeled into an outflow by the Blandford & Znajek (1977) mechanism from a radiation-pressure-dominated disk has been studied by Ghosh & Abramowicz (1997), who show the ratio of the jet power to the accretion luminosity is $\epsilon_{\rm j} = 3.2\times 10^{-2}\dot{m}_{-1}^{-1}$ (equation 15 in Ghosh & Abramowicz 1997). This is consistent with $\epsilon_{\rm j} \propto \dot{m}^{-0.65}$ from blazars statistics (Wang et al. 2004). The kinetic energy of the jet during the entire accretion is given by

$$E_{\rm K} = \epsilon_{\rm j} E_{\rm acc} = 2.4\times 10^{52}\ \epsilon_{0.42} M_8\ {\rm erg}, \tag{8}$$

where $\epsilon = 0.42\epsilon_{0.42}$ is the accretion efficiency for a black hole with spin $a = 1$. We note that the dependence of the kinetic energy on the black hole mass is determined by $\epsilon_{\rm j}$.

The interaction between the jet/outflow and the hot gas involves many micro-physical processes. Detailed calculations of the heating processes due to these interactions are beyond the scope of the present paper. However, we can easily estimate the location of the cavities from the jet/outflow energy. The outflow is sharply decelerated when the thermal energy of swept up and shocked ambient gas equals the initial kinetic energy of the outflow. Therefore $M_{\rm j}v^2 \approx \pi\Theta^2 R^3 n_e m_p c_{\rm s}^2/3$, where Θ is the opening angle of the outflow, c_s is the sound speed, v is the velocity of the jet/outflow, m_p is the proton mass and $M_{\rm j}$ is the mass of the outflow. The location of the cavities is then $R \approx 4.2(\Theta/0.05)^{2/3} n_{-2}^{-1/3}(v_{0.1}/c_{s,2})^{2/3}(\xi_{0.5}m_*)^{1/3}$ kpc, where $c_{s,2} = c_s/100\ {\rm km\ s^{-1}}$, $v_{0.1} = v/0.1c$ and c is the light speed. This radius is consistent with *Chandra* observations. Without specifying mechanisms, the time for the outflow from the black hole to dissipate its kinetic energy is

$$t_{\rm heating} = 1.7\times 10^5 R_{\rm 5kpc} v_{0.1}^{-1}\ {\rm yr}, \tag{9}$$

where $R_{\rm 5kpc} = R/5$kpc. Cavities of heated gas expand until pressure equilibrium is reached with their surroundings, $n_c T_c = n_h T_h$. From the brightness contrast of observed X-ray images the cavities are characterized by $f n_c^2 T_c^{1/2} = n_h^2 T_h^{1/2}$ where $f > 1$, and the subscripts of c and h refer to cavity and hot gas, respectively. At this time, $T_c > T_h$ and $n_c < n_h$ hold. The equilibrium continues until the cavities cool ' by bremsstrahlung. The lifetime of X-ray cavities is thus determined by the cooling time,

$$t_{\rm ff} = 1.8\times 10^9 T_7^{1/2} n_{-2}^{-1}\ {\rm yr}, \tag{10}$$

where $T_7 = T/10^7$K. Since the cooling timescale is much longer than the heating, cavities formed by successive stellar captures will merge, i.e., the energy injected in the cavities will pile up. The total kinetic energy released by the tidal disruption of a series of stellar captures by the black hole is given by

$$E_{\rm K}^{\rm tot} = \sum_{i=1}^{n} E_{\rm K}^i; \quad \text{and} \quad n = \dot{N}\min(t_{\rm G}, t_{\rm ff}), \tag{11}$$

TABLE 1.
STAR CAPTURES AND CAVITIES IN ELLIPTICAL GALAXIES

Name	σ (km s^{-1})	Ref.	Age (Gyr)	Ref.	$\log M_{\rm BH}$ ($M_\odot$)	$\dot{N}(\times 10^{-5})$ (yr^{-1})	$E_{\rm K}^{\rm tot}(\times 10^{56})$ (erg)	$P\Delta V(\times 10^{56})$ (erg)	R (kpc)	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NGC 708 (A 262)	241	1			8.46	1.44	17.8	4.25	6.5	3,5
NGC 4472	273	2	8.5	7	8.67	6.31	128	0.013	3.6	4
NGC 4636	180	2			7.95	0.447	1.71	0.24	5.1	6

REFERENCES: 1. McElroy (1995); 2. Merritt & Ferrarese (2001); 3. Blanton, et al. (2003); 4. Biller, et al. (2004); 5. Birzan, et al. (2004); 6. Ohto, et al. (2003); 7. Terlevich & Forbes (2002)

where n is the total number of star-capture events during time $\min(t_{\rm ff}, t_{\rm G})$, $t_{\rm G}$ is the lifetime of galaxies, and $E_{\rm K}^i$ is the kinetic energy released in event i. When $t_{\rm ff} \le t_{\rm G}$, some of the cavities produced by the outflow disappear. The radius of the cavity can be simply estimated by $P\Delta V = E_{\rm K}$, where P is the pressure of the hot gas and ΔV is the volume of the cavities. We have

$$\Delta R \approx \left(\frac{3E_{\rm K}^{\rm tot}}{4\pi P}\right)^{1/3} \approx 3.87\, E_{56}^{1/3} n_{-2}^{-1/3} T_7^{-1/3}\ {\rm kpc}, \qquad (12)$$

where $E_{56} = E_{\rm K}^{\rm tot}/10^{56}$ erg.

We note that $\max(t_{\rm rad}, t_{\rm cir}, t_{\rm acc}) \ll 1/\dot{N}_{\rm RG} \sim 10^5$ yr. This means that the feedback to the hot gas is impulsively episodic, not continuous. In summary this model involves two initial steps: 1) a red giant star is captured and 2) formation of an accretion disk from its debris. The first step depends on stellar evolution in the galaxy and the second involves hydrodynamical processes that eventually produce jets/outflows. We stress here that these assumptions may be improved and refined in the future by more detailed comparisons with observations, but currently available data is sufficient to support the viability of this model for cavity production.

3. APPLICATIONS AND DISCUSSIONS

Table 1 lists properties of hot gas cavities in three elliptical galaxies observed with *Chandra*. These "ghost" X-ray cavities are in relatively radio-quiet galaxies and are thus not caused by powerful jets as observed in radio-loud galaxies and quasars. Col (1) gives the name of the elliptical; Col (2) lists the stellar velocity dispersion σ in the galaxies; Col (3) lists the references for σ; Col (4) provides the lifetime of the galaxy if it has been estimated in the published references given in Col (5); Col (6) provides the black hole mass estimated from $\log M_{\rm BH}/M_\odot = 8.13 + 4.02 \log\left(\sigma/200{\rm km\ s^{-1}}\right)$ (Tremaine et al. 2002); Col (7) provides the capture rates taken from Syer & Ulmer (1999) or estimated from equation (2); Col (8) gives the total kinetic energy released by red giant captures during the galactic lifetime $t_{\rm G}$ or cooling timescale based on equation (11); Cols (9) and (10) show respectively the work done to created the cavities and the distance of the cavities from the center estimated from *Chandra* images; Col (11) gives the relevant references.

NGC 708 is a cD galaxy at the center of cluster A 262. It has a fairly faint double-lobed FR I radio morphology with a radio power $P_{1.4} = 4.7 \times 10^{22}$ W Hz^{-1} at 1.4 GHz (Blanton et al. 2004), indicating that this galaxy has not undergone a long-term radio-loud phase. Its VLA image is coincident with the X-ray cavities (Blanton et al. 2004). Table 1 shows that the feedback energy released by accretion onto the black hole of $10^{8.46} M_\odot$ is sufficient to power the formation of the "ghost" cavities. *NGC 4472* is a giant elliptical galaxy in the Virgo cluster with a faint radio jet/lobe similar to NGC 708. The red giant capture rate estimated by Syer & Ulmer (1999) is $10^{-4.2}$ yr^{-1}, which is relatively high. The feedback energy given in Table 1 is much larger than the work required to form the X-ray cavities. The giant elliptical *NGC 4636*, which is on the outskirts of the Virgo cluster, shows no evidence of radio jet/lobes. Ohto et al. (2003; see also O'Sullivan et al. 2005 for more details) revisited the *Chandra* ACIS data and showed that there are symmetric X-ray cavities along the south-west to north-east direction. They argue that the cavities are caused by the nuclear activities with a timescale of $\sim 10^3$ yr. Ongoing captures of red giant stars by the central black hole in NGC 4636 can explain the X-ray cavities in the surrounding gas.

The detailed hot gas morphologies indicate that the cavity formation process is more complicated than the model presented here. Our red giant capture rates are calculated by simplifying several important processes in Syer & Ulmer (1999) such as for example our assumption of a simple stellar evolution model with a constant lifetime for red giant stars ($t_{\rm RG} \sim 7 \times 10^8$ yr). We take the average radius of the red giant during its lifetime, while in reality the capture process will depend in detail on the evolutionary phase of the giant star. These simplifying assumptions lead to uncertainties when applied to individual galaxies. A key test to support or verify the capture model would be observations showing radio jets that appear simultaneous with X-ray flares in galaxies.

4. CONCLUSIONS

The highly disturbed hot gas in elliptical galaxies implies a short active history of the black holes. Captures of red giant stars and the feedback from their debris can explain the short activity timescales that create cavities in the hot gas and we show quantitatively that such a process may work in elliptical galaxies. An advantage of the present model is that red giant captures are a natural process that can trigger short-lived activity near the black hole. In particular, the accumulation of feedback energy resulting from successive red giant captures can explain the cavities observed in elliptical galaxies. This can be done in the absence of powerful, long-lived ($\sim 10^8$ year) radio emission. Further, more detailed studies of the red giant capture process are likely to suggest additional observational consequences.

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